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MEASUREMENT OF THE MECHANICAL AND DYNAMIC CHARACTERISTICS OF RUBBER

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ABSTRACT

This article describes an apparatus for determining /94*
the dynamic modulus of elasticity and the angle of mechanical losses of rubber in the 20 - 300 cps frequency range and the -20 - +150° C temperature range under deformation conditions of uniaxial contraction-extension. Three independent methods are employed. AUTHOR

There are two methods for determining the mechanical impedance by means of an electrodynamic converter: the reaction method and the method of "force and velocity" (Ref. 1). Apparatus employing the first method may be very simple (Ref. 2) (Ref. 3), but they have several significant disadvantages over the others: (a) a sharp increase in measurement error when the converter mobile system departs from the resonance frequency; (b) the influence of electric losses in the metallic sections of the converter on the accuracy with which the motion impedance is determined. Devices employing the second method are more complex, and require two converters with an over-all mobile system (a dual electrodynamic converter), but they are significantly free from the disadvantages mentioned above.

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* Note: Numbers in the margin indicate pagination in the original foreign text.

Marvin, Fitzgerald, and Ferry (Ref. 4) developed a device for dynamic tests of rubber; this device employed the method of "force and velocity". They proposed a corresponding electric measuring system. The latter two authors subsequently (Ref. 5) greatly improved both the converter and the measuring system, replacing the inconvenient compensating device by an alternating-current bridge.

This article describes this type of device; however, in operation it is simpler and more convenient.

Description of the Device

This device employs the GMV-1 type of factory "generator of mechanical vibrations". Figure 1 shows a transverse cross section of the GMV, together with the mechanical units for fastening the sample of rubber being studied, the heater, and the sample. The driving coil 1 is rigidly fastened to the driven coil 3 by an aluminum connecting rod 2. Each coil is located in the radial constant magnetic field of its magnetic system.[(1)] The coils are suspended by means of textolite washers. Periodic amplification (maximum amplitude of 500 g) is transmitted through the plunger 4 to the sample of rubber being studied 5. As a result of this, the sample - one side of which is fastened to the mounting 6-is subjected to deformation of uniaxial compression-extension. The sample is initially tightened against the plunger by moving the mounting 6. The GMV and the mechanical units of the device are strengthened by a welded support made of corner iron embedded in the principal wall. To a certain extent, this decreases the parasatic vibrations of the apparatus.

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(1) As tests have shown, the GMV-1 second magnetic system serves simultaneously as a good magnetic screen between the coils, which avoids the necessity of compensating for the mutual inductance effect, in contrast to (Ref. 1, 5).

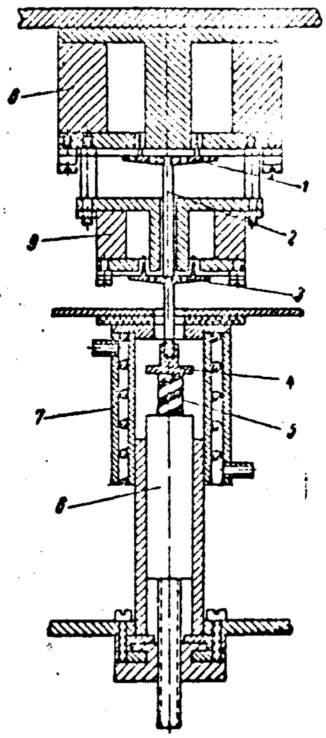

Figure 1

Transverse Cross Section of the Device

1 - Driving coil; 2 - Coupling rod; 3 - Driven coil;
4 - Plunger; 5 - Sample of material being studied;
6 - Mounting; 7 - Housing; 8 - First magnetic system;
9 - Second magnetic system.

In order to produce the requisite temperature, the housing 7 was used /95 during the measurements; the working fluid was deflected along this housing by an ultrathermostat. The working fluid was either water or ethyl alcohol. When heating was performed above 100°C, an electric oven was employed. For cooling below -10°C, liquid nitrogen was delivered to the housing by means of a simple device. The sample temperature was measured by a constantan-copper thermocouple within an accuracy of 0.5°C. The thermocouple was usually placed on the mounting with the sample. A control thermocouple placed inside the sample made it possible to determine that the difference between the readings of both thermocouples disappeared after 20 minutes at the given temperature.

Electric Measuring System

In contrast to (Ref. 5), this device employs a more convenient system of an alternating current bridge (Figure 2), thus providing a separate reading of the real and imaginary part of the electric impedance of the driven coil Z_v, as can be seen from the equations of balance for the bridge:

$$R_v = C_3 R_2 / C_4 \quad \text{and} \quad L_v = C_3 R_2 R_4,$$

in which the product C_3R_2 was chosen as constant. The fact that the equations of balance do not depend on frequency, and the computational simplicity which this entails, greatly simplifies tests in series.

The bridge is connected in parallel to a circuit consisting of purely ohmic resistance R_A which is switched on in series with the driving coil Z_f. An oscillograph serves as a balance indicator. This makes it possible to distinguish the useful signal from the background caused by the parasite vibrations of the apparatus, and from higher harmonics resulting from the magnetic circuit iron. The apparation of the bridge was checked by measuring the sample coil inductances. It was found that the error entailed in measuring the standard parameters did not exceed 1% at frequencies of 20-500 cps.

The mechanical impedance of the converter Z_M is related to the electric relationship which can be measured (Ref. 5):

$$Z_M = (B_1 l_1 r + B_2 l_2) / (Z_v - Z_v^0) B_2 l_2,$$

where B and l represent the magnetic field induction in a circular air gap and the length of the coil conductor (the letter 1 refers to the driving coil; 2 - the driven coil). Z_v^0 is the eigen electric impedance of the driven coil which, generally speaking, depends on frequency and temperature. If $R_A \gg |Z_f|$, $R_2 \gg |Z_v|$, then $r = I_1/I_2 \simeq R_2/R_A$, where I_1 and I_2 represent the currents

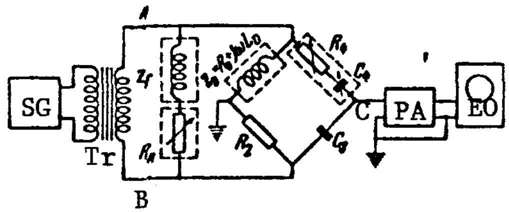

Figure 2

Principal Electric Diagram of the Apparatus

R_4 (0-11—111 ohms) and C_4 (0-1.1111 mkf) Units of the MDP bridge; R_2 (10^4-10^5 ohms) - Magazine of non-reactive resistances MCB-49; $C_3 = 10^{-3}$ mkf - KCO-5 type of mica condenser; R_A (10^3-10^5 ohms) -Magazine of BC-2 resistances; SG - SG-10 Sonic frequency generator; Tr - Matching transformer; PA - preliminary amplifier; EO - EO-4 Oscillograph.

passing through the driving coil and the driven coil, respectively. In our case, R_2 changes from 10^4 to 10^5 ohms, and R_A changes from 10^3 to 10^5 ohms. $|Z_v|$ never exceeded 150 ohms, even in the frequency region of the system mechanical resonance, and $|Z_f|$ - 70 ohms so that the above conditions are always fulfilled.

It is necessary to completely brake the mobile converter system in order to measure Z_V^0 directly. In order to avoid this, Z_M is determined from two subsequent measurements of Z_V carried out at different r (method I) or at different coil switchings (method II). In the first case, we have

$$Z_M = K^2 (r' - r'') / (Z_v' - Z_v'') = K^2 / Z \, . \tag{1}$$

In the second case we have

$$Z_M = K^2 \cdot 2r / (Z_{vc} - Z_{vb}) = K^2 / Z_e . \tag{2}$$

The letter c designates the matched switching; b indicates the opposite switching. In order to obtain the greatest possible accuracy, the difference between the electric impedances to be measured must be made as

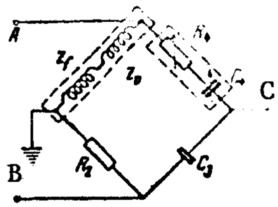

Figure 3

Electric Measuring System for Determining Z_M According to the Third Method

Points A, B, C correspond to the same ones in Figure 2.

large as possible by the appropriate selection of r.

A method similar to the method for determining the mutual inductance /96 coefficient may also be used to determine the mechanical impedance on a dual electrodynamic converter. In this case, the circuit bypassing the bridge is removed, greatly complicating its adjustment. Both coils which are connected in series are switched on in the measuring arm of the bridge (Figure 3). The total electric impedance of both coils is thus the quantity being determined; with the matched switching, this equals

$$Z_c = Z_v^0 + Z_f^0 + (B_1 l_1 + B_2 l_2)^2 / Z_M,$$

and for the opposite switching, this equals

$$Z_B = Z_v^0 + Z_f^0 + (B_1 l_1 - B_2 l_2)^2 / Z_M,$$

where Z_f° is the eigen electric impedance of the driving coil.

By subtracting the second equation from the first, we obtain

$$Z_M = K^2 \cdot 4/(Z_c - Z_B) = K^2/Z_e \quad (3)$$

<u>Checking the Apparatus Operation</u>
<u>Determination of K^2</u>

The computational formulas are based on the assumption that all of the mechanical elements of the vibrating converter system are connected at the

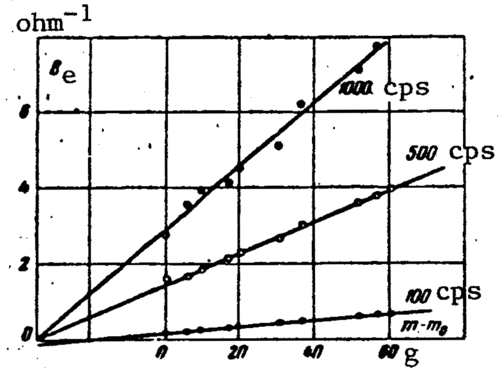

Figure 4

Dependence $B_e = f(m)_\omega$ for Three Frequencies.

The lines obtained for 500 and 1000 cps intersect the abscissa axis at the point m = 0, according to the equation $B_e = \omega m/K^2$. The section delineated on the B_e axis of the line obtained at 100 cps is proportional to $S_o/\omega K^2$; m_o - the eigen mass of the GMV mobile system. The point $m - m_o = 0$ corresponds to the beginning of reading the combined masses.

joints, i.e., its equation of motion has the following form:

$$Z_M^0 = R_M^0 + j(\omega m - S_0/\omega), \tag{4}$$

where R_M^0, m and S_0 are the friction, mass, and elasticity, respectively: ω - the angular frequency. If equation (4) is valid, and since $Z_M = K^2/Z_e = K^2(G_e + jB_e)$, then $B_e = (\omega m - S_0/\omega)/K^2$, or at large frequencies $B_e \approx \omega m/K^2$; the quantity K^2 can be determined from the inclination of the line $B_e = f(m)_\omega$ or $B_e = f(\omega)_m$ (at large frequencies). Taking the possible dependence of K^2 on frequency into account, it is best to calibrate the device by changing the mass of the mobile system. Figure 4 presents the dependences for three frequencies. It can be seen that the experimental points lie directly on straight lines. The increased scatter of the points pertaining to the frequency of 1000 cps indicates that when the frequency increases, the accuracy with which the mass is measured decreases.

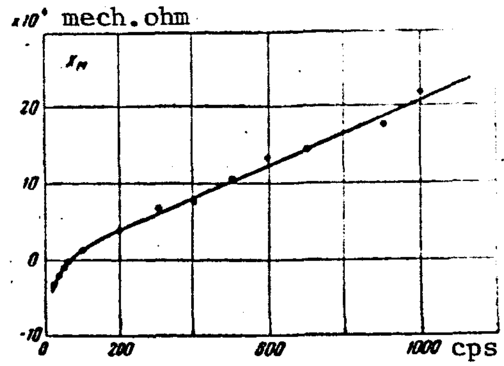

Figure 5

In addition to K^2, it is also possible to determine the eigen mass and elasticity of the mobile system from the above dependences. We obtained the following values: $K^2 = (7.4 \pm 0.1) \cdot 10^4$ ohms g/sec; $m_0 = (3.37 \pm 0.3)$ g; $S_0 = (6.65 \pm 0.3) \cdot 10^6$ dyn/cm. The mobile system was weighed, and $m_0 = 33.9$ g was obtained. Experiments on static loading - $S_0 = 6.7 \cdot 10^6$ dyn/cm.

Figure 5 compares the theoretical dependence of $X_M = \omega m_0 - S_0/\omega$ on frequency with experimental data. It can be seen that the experimental points closely follow the curve up to 200 cps. At higher frequencies, the scatter is greater, but it does not exceed 5%.

Thus, the reactive part of the mechanical impedance is correctly determined by equation (4). According to theory, if the quantity R_M^0 is not /97 constant, then at least it is positive. However, this prediction is only valid up to 150 cps, while beyond this R_M^0 - computed from equations (1), (2), and (3) - passes through zero and assumes a negative value (Figure 6).

One positive feature of the apparatus is the possibility of determining $Z_e = R_e + jX_e$, and consequently Z_M, by three different methods which control each other. This control was performed, and showed complete agreement between

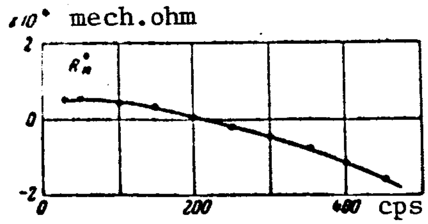

Figure 6

the results (Table 1). This indicates that the anomalous frequency dependence of R_M^0 is caused by phenomena taking place in the transformer itself, but to no extent in the measuring system. In our device, it is primarily caused[2] by parasitic currents formed in the aluminum frames of the GMV-1 coils which had not been slotted sufficiently. Due to this fact, the electromechanical coupling coefficient became a complex quantity.

TABLE 1

ν, cps		Method I	Method II	Method III
200	$R_e=$	0,00	0,00	0,00
	$X_e=$	—1,89	—1,885	—1,89
500	$R_e=$	—0,11	—0,11	—0,11
	$X_e=$	—0,63	—0,63	—0,63
1 000	$R_e=$	—0,16	—0,15	—0,15
	$X_e=$	—0,28	—0,275	—0,28

In connection with the fact that the mechanical losses in rubber are comparitively large, it can be disregarded in the frequency range where the anomaly R_M^0 is insignificant. This complication leads to the fact that measurements above 300 cps become quite inaccurate.

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(2) The reasons for and patterns of this phenomenon, as well as the information on it in the literature, will be examined in detail in a separate article.

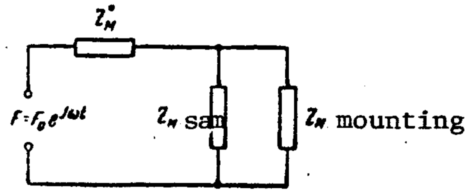

Figure 7

Determining the Material Characteristics

If Z_M is the converter impedance with the sample of material being studied, and Z_M^0 is the converter impedance without it, then the sample impedance is[3] $Z_{M\ sam} = Z_M - Z_M^0$. If we know the sample impedance, we can determine the complex modulus of the material

$$E^\bullet = j\omega D Z_{M\ sam} = j\omega D(R_{M\ sam} + jX_{M\ sam}),$$

where D is the geometric coefficient of the sample. In the case of cylindrical samples $D = 4l/\pi d^2$, where l is length, and d is sample diameter.[4]

If we employ the heat model of Kelvin-Voigt as the computational system, we obtain the following expression for the dynamic elasticity modulus: $E = \omega D X_{M\ sam}$, and for the dynamic viscosity coefficient - $\eta = DR_{M\ sam}$.

The tangent of the mechanical loss angle tg $\delta_M = R_M/X_M$ does not depend on the sample coefficient, and can therefore be determined with greater accuracy than the quantities indicated above.

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(3) The combination of the mechanical impedances of the system and of the sample in a unit correspond to the sample located between the plunger and the mounting.

(4) In order to determine the elasticity modulus more accurately, it is necessary to introduce a correction for the end effects which allow for the influence of dry friction on the end faces of the sample, which interferes with the latter being freely deformed in these cross sections.

The measurement errors will be less when the sample impedance is great. However, in the case of very rigid samples, it is necessary to allow for the mounting impedance, which can be determined experimentally by attaching the plunger to the mounting, and to perform a computation employing the equivalent electric system shown in Figure 7. It is difficult to make an accurate determination of the mounting impedance.

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